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OF

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NEW TENTOR

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Indholdsfortegnelse

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1. Introduction

Formerly a great part of the steel used for reinforcement of concrete structures with strength about 550 Mpa was manufactured by hot rolling folowed by a cold working process. This process of production was relatively expensive, therefore, in the nineties a new pocess of production was employd.

In the new process the steel bars are still manufactured by hot rolling, but when the steel bars leave the last stand of rollers with a temperature of about 1000° C, they are led through cooling tubes where controlled amounts of water under high pressure are sprayed on the steel face. By this treatment the cooling of the steel face is accelerated and it obtains a martensitic hardening structure. At that time the inner core is austenitic. When the steel bars leave the cooling zone the surface temperature is about 300° C. The heat in the core of the steel bars will during the cooling process in the atmospheric air penetrate the outer shell and hereby temper the martensite. The result will be a steel bar with a ductile core of ferrite and perlite, a transition zone and an outer shell of tempered martensite.

The ribbed reinforcing bars - *New Tentor* - are produced in the last decribed way at *The Danish Steel Work Ltd* in Frederiksværk.

This report deals with fatigue tests of reinforcing ribbed bars (rebars) – *New Tentor* . As a result of the tests the relationship between the number of cycles N and the stress range $\Delta\sigma = \sigma_{max} - \sigma_{max}$ of constant magnitude, which under the given conditions leads to fatigue failure, is found and shovn in S-N curves. S denotes here the stress range $\Delta\sigma$.

2 Test specimens

The tests include 29 rebars with the diameter ϕ = 10 mm and the length 590 mm and 33 rebars with the diameter ϕ = 16 mm and the length 600 mm. All the rebars are marked with a number. To avoid failure in the rebars where the grips of the testing machine clutch the rebars all the rebars were equipped with aluminium tubes at either end. For rebars ϕ 10 and ϕ 16, the aluminium tubes have the dimensions $l \times d_y \times d_i$ = 100 x 18.0 x 11. 8 mm and $l \times d_y \times d_i$ = 85 x 23.8 x 18.0 mm, respectively, where l, d_y and d_i are the length, the outer and the inner diameter, respectively. The cavity between the rebar and the aluminium tube was filled with a two component glue, Araldite 2011 (AVV106) + Araldite 2011B (HV 953U).

In figures 1 and 2 photos of the 500 kN hydraulic testing machine with a test specimen (ϕ= 10 mm) and a rebar with an aluminium tube between the rebar and the grips of the tesing machine are shown, respectively.

Original rebars with the diameter ϕ = 25 mm were included in the test programme. Tests were carried out with 11 test specimens. In all test specimens the failure occured where the grips of the testing machine clutch the rebars. Therefore the rebars with ϕ = 25 mm are, for the time being, removed from the test programme.

Figure 1 500 kN hydraulic testing machine with a testspecimen (ϕ = 10 mm) after rupture.

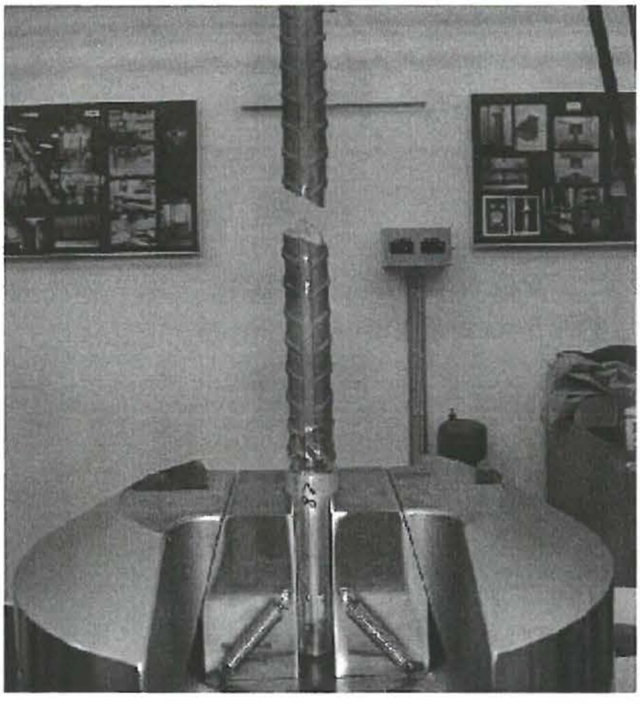


Figure 2 Photo of a rebar with an aluminium tube between the rebar and the grips of the testing machine.

3 Material properties

The chemical composition of the heats from which the rebars are picked out is shown in table 1 where Ceq = Carbon-Equivalent

Table 1 Chemical composition of the heats

Diameter ϕ [mm]	C [x10^{-4}]	Mn [x10^{-4}]	Si [x10^{-4}]	P [x10^{-5}]	S [x10^{-5}]	Cr [x10^{-4}]	Cu [x10^{-4}]	Ni [x10^{-4}]	Mo [x10^{-4}]	N [x10^{-6}]	Ceq [x10^{-4}]
10	21	82	24	28	15	13	21	8	1	123	40
16	21	81	25	20	21	9	29	8	1	79	39

To obtain the material properties of the rebars, static tests were performed with 3 bars of each diameter. The mean values of the properties are shown in table 1.

Table 2 Material properties for the reinforcement

Diameter [mm]	Initial modulus of elasticity [MPa]	Yield strength [MPa]	Ultimate strength [MPa]	Non-proportional elongation at maximum force [%]
10	220x10^3	628	722	10.2
16	188x10^3	628	714	10.4

4 Test equipment

A 600 kN Mohr-Federhaff universial testing machine (MF) and a 500 kN servohydraulic testing machine (MTS) was applied for the static and the fatigue testing of the rebars, respectively. The latter is shown i figure 1. The MF and the MTS testing machines are equipped with mechanical and hydraulic fastening grips, respectively.

5 Testing

Static testing

The test specimens were instrumented with inductive displacement transducers and during the test corresponding values of force and elongation were measured and data-acquisition was applied. Stress, strains and modulus of elasticity were calculated in a MATLAB programme. The static tests were force controlled corresponding to at constant stress increase of approximately 7 MPa/sec. Examples of representative stress-strain diagram for the rebars ϕ = 10 mm and ϕ = 16 mm are shown in figure 3 and 4 respectively.

Fatigue testing

All the fatigue tests were force controlled. The variation of the force was harmonic and the stresses were oscillating between constant values of σ_{max} and σ_{min}. In many of the tests the test machine was stopped for a few minutes once or a couple of times to correct the force influence. During the fatigue testing, values of the minimum force, the maximum force, the minimum and maximum grip stroke were measured for every 1000 cycles.

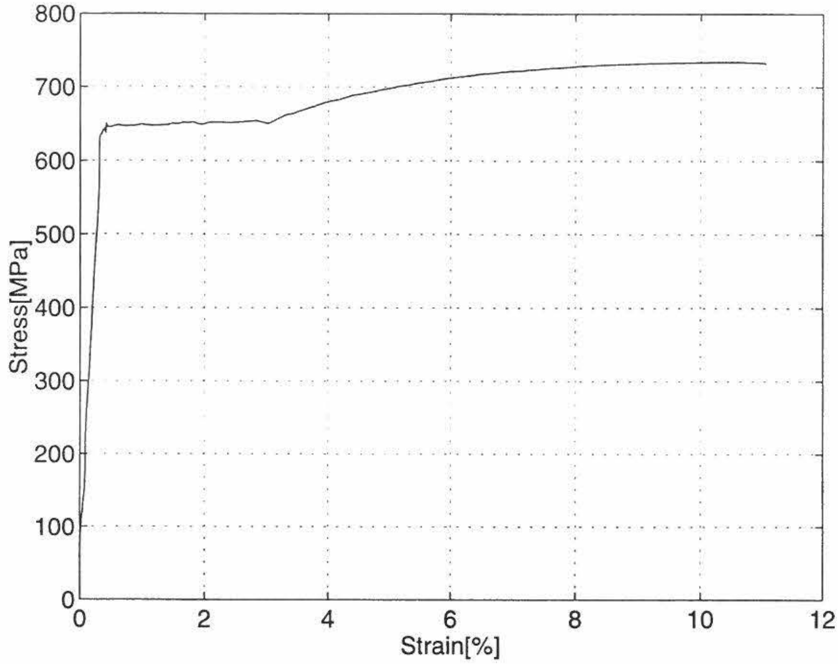


Figure 3 Representative stress-strain diagram of a rebar ϕ =10 mm.

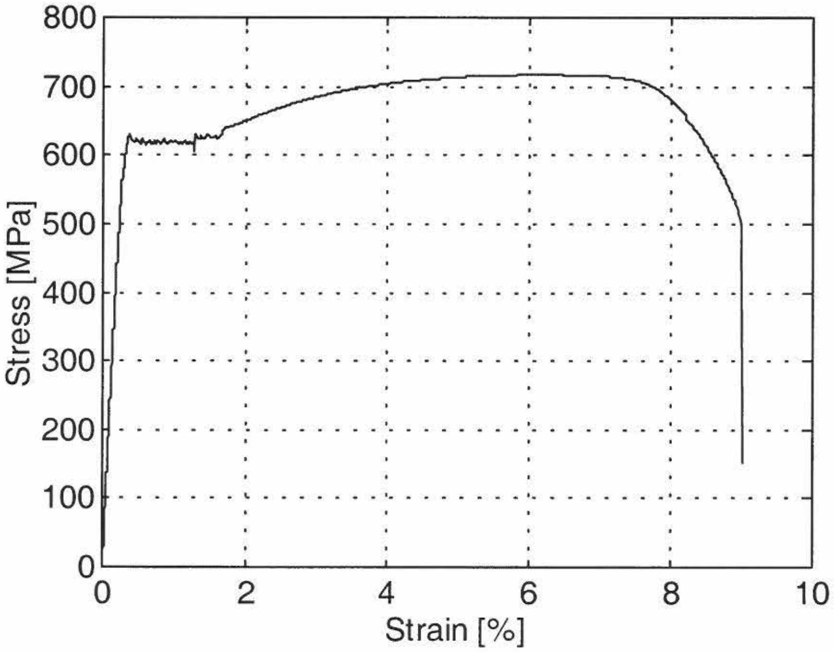


Figure 4 Representative stress-strain diagram of a rebar ϕ = 16 mm

Rebars ϕ = 10 mm: For all rebars, the test frequency was 10 Hz, the average stress $\sigma_m = 0.5(\sigma_{max} + \sigma_{min})$ was within the interval 299 MPa < σ_m < 322 MPa and the stress range $\Delta\sigma = \sigma_{max} - \sigma_{min}$ in the interval 259 MPa $\leq \Delta\sigma \leq$ 564 MPa. The test results are shown in table 4.

Rebars ϕ = 16 mm: For this diameter, frequencies of 5, 10 and 15 Hz were used. With so low frequencies, the frequency seems to have no influence on the result. For these rebars the average stress σ_m was within 4 different intervals, see table 3. The test results are shown in table 5.

Table 3 Intervals for the average stress $\sigma_m = 0{,}5(\sigma_{max} + \sigma_{min})$ for rebars ϕ = 16 mm

Number of specimens	Intervals for $\sigma_m = 0{,}5(\sigma_{max} + \sigma_{min})$ [MPa]	Symbols
3	257 MPa $\leq \sigma_m \leq$ 283 MPa	*
22	300 MPa $\leq \sigma_m \leq$ 315 MPa	+, o and x
6	317 MPa $\leq \sigma_m \leq$ 337 MPa	□
2	392 MPa $\leq \sigma_m \leq$ 395 MPa	▽

In more of the tests the failure occurred very close to the grips. Only results from tests where the failure occurred at a distance of more than 2ϕ from the grips are included in this report.

6 Test results and discussion

Rebars ϕ = 10 mm

As an example on the accumulated test results the variation of σ_{max}, σ_{min}, $\Delta\sigma = (\sigma_{max} - \sigma_{min})$, and $\sigma_m = 0{,}5(\sigma_{max} + \sigma_{min})$ during the test are shown in figure 5.

In figure 5, it is seen that the test machine was stopped at about N_1 = 29000 and N_2 = 55000 cycles in order to correct the force influence. After the last correction it is seen that the stresses are nearly constant until failure in the test specimen at N_u = 330048 cycles.

In figure 6 the fatigue strength curve (S-N curve) for rebars ϕ = 10 mm is shown. In the test series failure in the rebars did not occur for values of $(\sigma_{max} - \sigma_{min})$ lower than 286 MPa. Test specimens no. 45 with $(\sigma_{max} - \sigma_{min})$ = 259 MPa reached N = 10,000,003 cycles without failure and test specimens no. 46 with $(\sigma_{max} - \sigma_{min})$ = 277 MPa reached N = 12,257,540 cycles without failure. These two test results are indicated by o in figure 6.

29 test results are shown in figure 6 and by linear regression a straight line for these tests (except for the two tests without failure) is calculated. The equation for the straight line in figure 6 is

$$\log(\sigma_{max} - \sigma_{min}) = 3.796 - 0.2264 \log(N) \tag{1}$$

The equation for a straight line where all the test results are above the line is

$$\log(\sigma_{max} - \sigma_{min}) = 3.818 - 0.2403 \log(N) \tag{2}$$

The equation for the S-N curve given for reinforcing bars in the Danish code DS 411 is

$$\log(\sigma_{max} - \sigma_{min}) = 3.49 - 0.2 \log(N) \tag{3}$$

It is seen that the lower bound for the test results is above the S-N curve given for reinforcing bars in the Danish code DS 411.

Rebars ϕ = 16 mm

As an example on the accumulated test results the variation of σ_{max} , σ_{min} , $\Delta\sigma = (\sigma_{max} - \sigma_{min})$, and $\sigma_m = 0{,}5\ (\sigma_{max} + \sigma_{min})$ during the test are shown in figure 7.

In figure 8, the fatigue strength curves (S-N curves) for rebars ϕ = 16 mm are shown. In this test series failure in the rebars did not occur for values of $\Delta\sigma = (\sigma_{max} - \sigma_{min})$ lower than 388 MPa The test specimens no. 43, 44 and 45 with $\Delta\sigma$ equal to 340 MPa, 341 MPa and 388 MPa, respectively reached N = 4,418,891, N = 7,851,619 and N = 3,864,523 cycles, respectively, without failure. In test specimens no. 61 with σ_m = 307 MPa and $\Delta\sigma$ = 395 MPa indicated by + in figure 8 failure occurred at 8,749,622 cycles.

33 test results are shown in the figure and by linear regression, a straight line for these tests exclusive the test results indicated by + and o are calculated. Last-named (3 test results) indicate tests where failure did not occurred. The equation for the straight line in figure 8 is

$$\log(\sigma_{max} - \sigma_{min}) = 3.5604 - 0.1686 \log(N) \tag{4}$$

As seen in table 2, four intervals for the average stress σ_m were used in this test series. It looks like the values of the stress range $\Delta\sigma = (\sigma_{max} - \sigma_{min})$ at failure are independent of the average stress σ_m except for very high values of σ_m, where the tendency is that higher values of σ_m will give lower values of $\Delta\sigma$ for the same value of number of cycles N. See the two test results indicated by $\triangledown$ in figure 8 and table 5.

Ignoring the two test results indicated by $\triangledown$, the equation for a straight line, where all the test results are above the line is

$$\log(\sigma_{max} - \sigma_{min}) = 3.5966 - 0.1802 \log(N) \tag{5}$$

It is seen that this lower bound for the test is above the S-N curve given for reinforcing bars in the Danish code DS 411, see equation (3).

Table 4 Test results from fatigue tests with rebars ϕ = 10 mmm

Fatigue tests with New Tentor, $\phi = 10$ mm, $A_{nom} = 79$ mm^2							
test speci-men no.	average value in MPa for				number of cycles N_u at rupture	frequency in Herz	comments
	σ_{max}	σ_{min}	$0,5(\sigma_{max}+\sigma_{min})$	$\sigma_{max}-\sigma_{min}$			
45	436,3	177,6	307,0	258,7	10.000.003	10	no rupture
46	444,7	167,5	306,1	277,2	12.257.540	10	no rupture
44	451,9	165,5	308,7	286,4	549368	10	
47	452,1	163,4	307,7	288,7	493.526	10	
43	463,1	143,0	303,0	320,1	318.288	10	
42	463,9	143,5	303,7	320,4	330.048	10	
41	487,3	133,1	310,2	354,3	190.311	10	
38	481,1	122,6	301,9	358,5	258.280	10	
40	485,6	124,0	304,8	361,6	214.466	10	
33	488,9	113,0	300,9	376,0	308.939	10	
30	494,8	117,4	306,1	377,4	231.156	10	
31	492,2	114,3	303,3	377,9	295.478	10	
29	500,6	110,5	305,6	390,1	200.895	10	
27	504,2	114,1	309,2	390,1	158.010	10	
28	501,4	111,1	306,3	390,4	285.769	10	
25	505,7	110,2	308,0	395,5	406.447	10	
26	509,8	112,4	311,1	397,4	186.977	10	
24	507,9	104,5	306,2	403,4	239.155	10	
62	512,3	86,8	299,5	425,4	253.308	10	
17	553,2	69,5	311,4	483,7	90.345	10	
39	548,2	64,0	306,1	484,2	116.748	10	
21	556,1	60,0	308,0	496,1	112.061	10	
23	548,4	49,5	299,0	498,9	82.812	10	
12	581,8	32,6	307,2	549,2	69.105	10	
14	591,3	52,9	322,1	538,4	48.948	10	
36	592,5	39,9	316,2	552,7	29.449	10	
58	579,0	24,4	301,7	554,6	57.976	10	
34	590,7	27,4	309,1	563,3	34.574	10	
35	587,5	23,8	305,6	563,7	31.369	10	

Table 5 Test results from the fatigue test with rebars $\phi = 16$ mm

Fatigue tests with New Tentor, $\phi = 16$ mm, $A_{nom} = 201$ mm^2							
test specimen no. and symbol	average value in MPa for				number of cycles N_u at rupture	frequency in Herz	comments
	σ_{max}	σ_{min}	$0,5(\sigma_{max}+\sigma_{min})$	$\sigma_{max}-\sigma_{max}$			
53 *	504,6	9,3	257,0	495,3	166.599	15	
55 *	545,5	9,8	277,7	535,7	139.074	15	
54 *	551,8	14,3	283,1	537,4	102.235	15	
43 o	478,2	138,7	308,4	339,5	4.418.891	15	no rupt.
44 o	478,0	137,0	307,5	341,0	7.851.619	15	no rupt.
45 o	505,2	117,4	311,3	387,8	3.864.523	15	no rupt.
61 o	504,0	109,0	306,5	395,0	8.749.622	15	
60 o	508,5	111,0	309,8	397,5	344.004	15	
51 o	508,7	102,7	305,7	405,9	574.669	15	
58 o	507,8	99,8	303,8	408,0	418.835	15	
59 o	508,7	98,4	303,5	410,3	356.789	15	
50 o	515,6	104,9	310,2	410,8	332,565	15	
49 o	510,5	91,1	300,8	419,4	395.631	15	
38 o	522,2	94,2	308,2	428,0	400.469	5	
39 o	526,1	93,0	309,5	433,1	270.410	10	
36 o	528,4	87,0	307,7	441,4	399.796	10	
35 o	591,8	31,6	311,7	560,2	76.750	5	
34 o	586,0	25,5	305,7	560,5	76.032	5	
27 o	594,7	24,1	309,4	570,5	52.820	5	
31 o	598,9	26,9	312,9	572,0	46.445	5	
29 o	594,5	22,2	308,4	572,3	45.948	5	
47	527,8	106,6	317,2	421,2	248.648	15	
41	539,0	105,5	322,2	433,6	214.453	10	
26	589,2	84,4	336,8	504,8	132.102	5	
19	584,1	78,4	331,2	505,8	128.323	5	
25	588,5	82,3	335,4	506,1	117.216	5	
23	581,1	74,6	327,8	506,5	151.378	5	
56 ∇	598,2	190,2	394,2	408,0	232.376	15	
57 ∇	595,6	188,7	392,2	409,6	246.083	15	

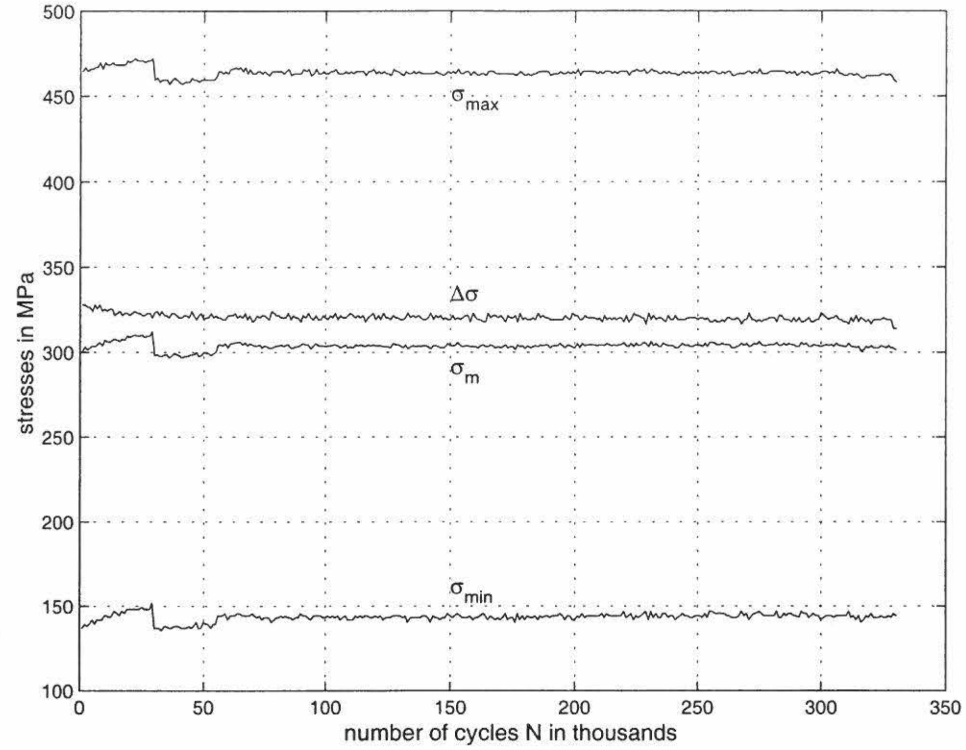


Figure 5 Stress curves from the fatigue test with rebar ϕ = 10, test specimen no. 42

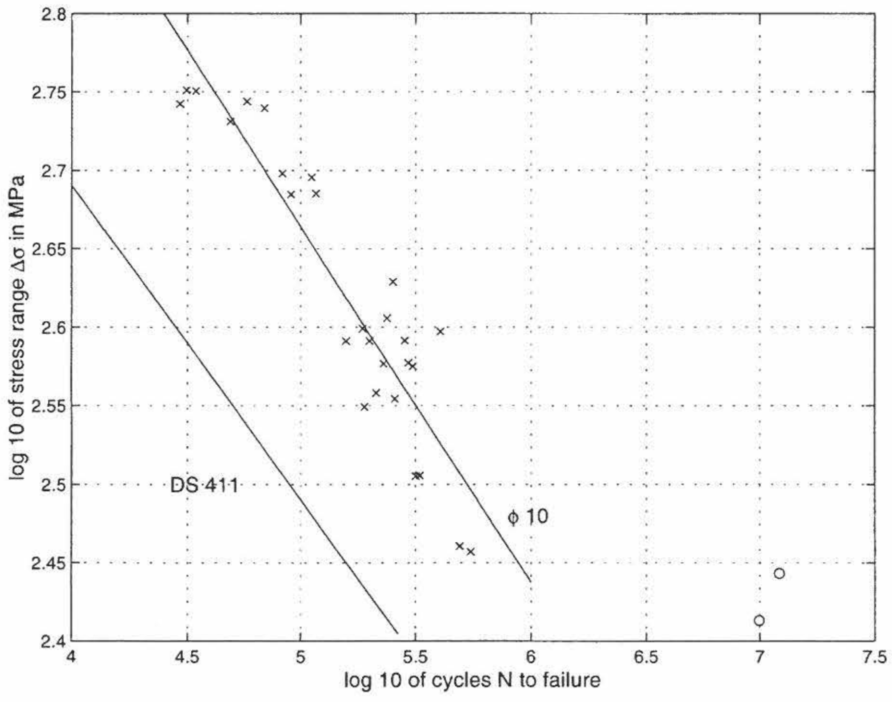
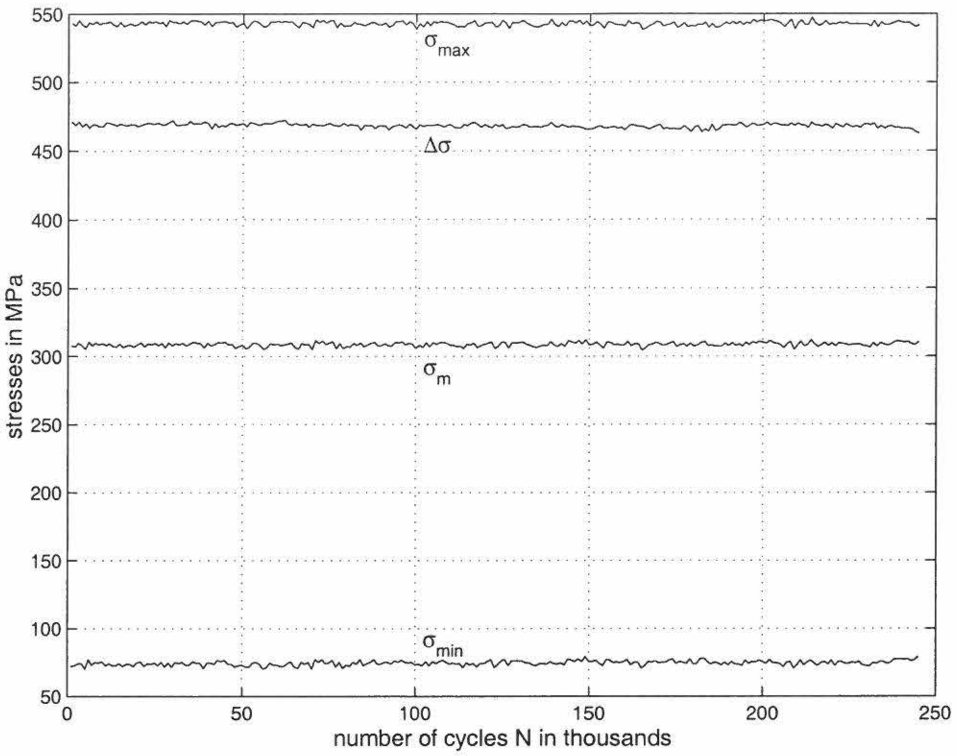


Figure 6 Fatigue strength curve (S-N curve) for rebars ϕ = 10 mm.



Figur 7 Stress curves from the fatigue test with rebars ϕ = 16 mm, test specimen no. 64

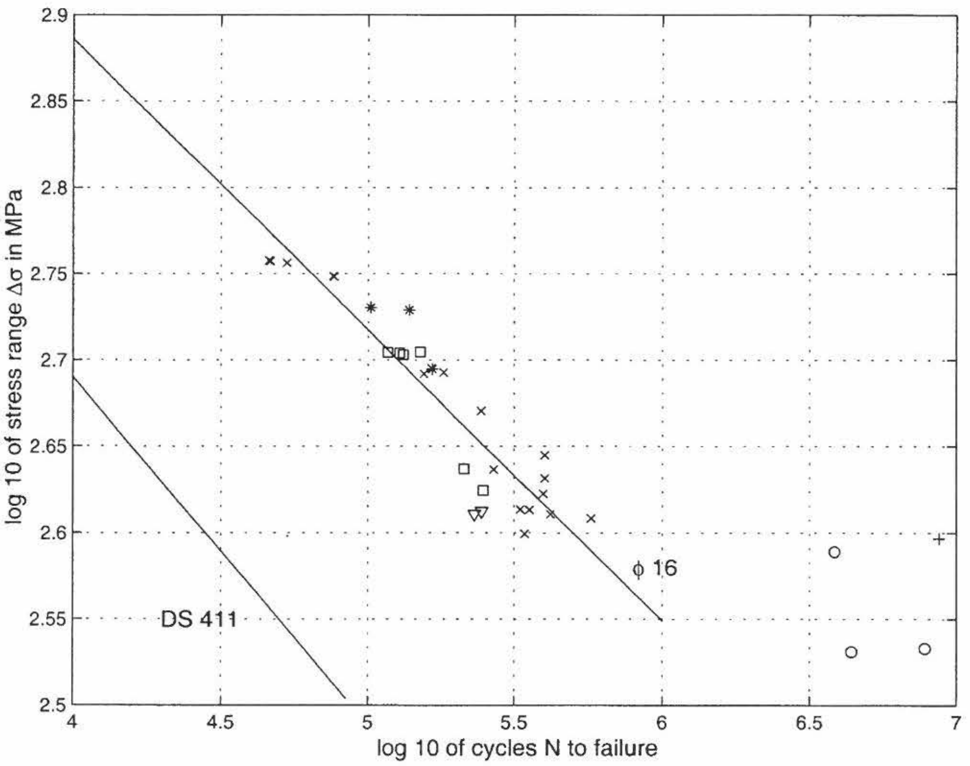
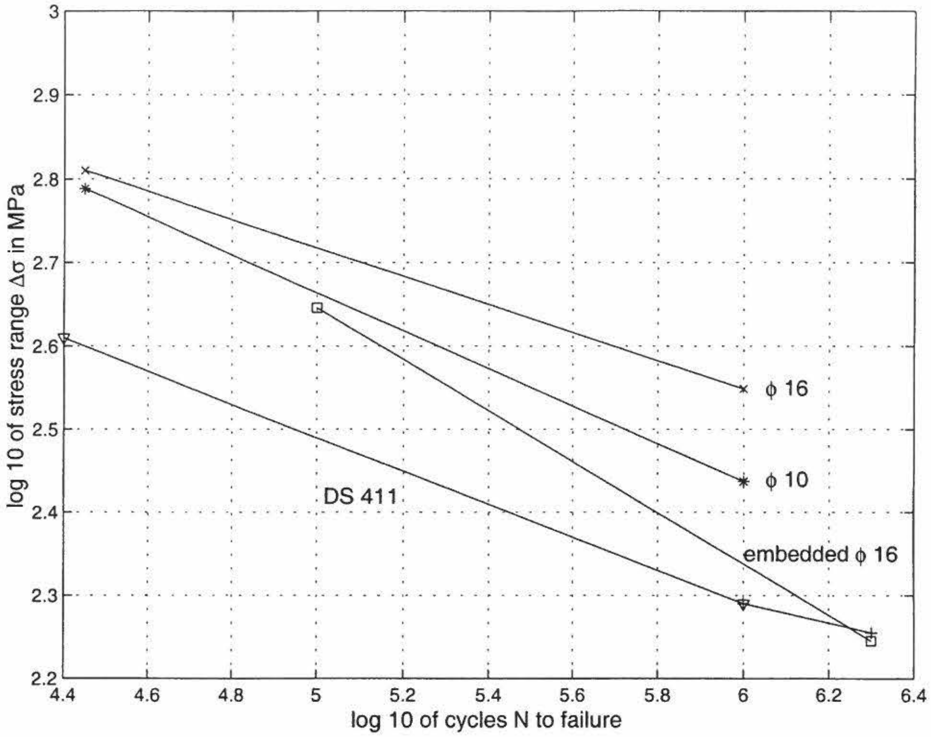


Figure 8 Fatigue strength curves (S-N curves) for rebars ϕ = 16 mm



Figur 9 *Fatigue strength curves (S-N curves) for New Tentor rebars ϕ = 10mm, ϕ = 16 mm, ϕ = 16 mm embedded in Densit Joint Cast ® and the S-N curve given in DS411.*

7. CONCLUSIONS

Figure 9 shows the by tests determined S-N curves for New Tentor rebars ϕ = 10 mm, ϕ = 16 mm, the S-N curve for embedded ribbed rebars ϕ = 16 mm (yield strength ~ 623 Mpa) and the S-N curves given in DS 411. It is seen that the S-N curve for rebars ϕ = 16 mm is situated above the S-N curve for rebars ϕ = 10 mm and both of them are situated above the S-N curve given in DS 411.

The S-N curve marked with □ shows fatigue tests with ribbed reinforcing bars ϕ = 16 mm embedded in Densit Joint Cast ®. These tests are carried out by Lars Pilegaard Hansen, Instituttet for Bygningsteknik, Aalborg Universitet and described in "Udmattelsesforsøg med ribbestål indstøbt i Densit Joint Cast ® " (in Danish)

8. ACKNOWLEDGMENT

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